

Bermudagrass Management in the Southern Piedmont USA: VII. Soil-Profile Organic Carbon and Total Nitrogen

A. J. Franzluebbers* and J. A. Stuedemann

ABSTRACT

Estimates of potential soil organic C (SOC) and total N (TN) sequestration at depths below the traditional plow layer (i.e., 0–0.3 m) in agricultural systems are needed to improve our understanding of management influences on nutrient cycling and potential greenhouse gas mitigation. We evaluated the factorial combination of nutrient source (inorganic, inorganic + cover crop, and broiler litter) and forage utilization (unharvested, hayed monthly, and low and high grazing pressure) on profile distribution of and changes in SOC and TN during the first 5 yr of 'Coastal' bermudagrass [*Cynodon dactylon* (L.) Pers.] management. Nutrient source did not affect SOC and TN in the soil profile. Contents of SOC and TN under haying were lower than under other management systems throughout the soil profile. Averaged across nutrient sources, SOC sequestration to a depth of 0.9 m was 3.6 Mg ha⁻¹ ($P = 0.06$) under low grazing pressure and 2.4 Mg ha⁻¹ ($P = 0.19$) under high grazing pressure. Sequestration of TN was 0.49 Mg ha⁻¹ ($P = 0.03$) under low grazing pressure and 0.56 Mg ha⁻¹ ($P = 0.02$) under high grazing pressure. The minimum change in SOC and TN needed to detect significant ($P = 0.1$) sequestration increased an average of 0.6 and 0.10 Mg ha⁻¹, respectively, for each additional 0.3-m layer of soil. This study demonstrated that plow-layer accumulation of SOC and TN occurred, but that increased variability with depth and small loss of SOC and TN with an additional 0.3 m below the plow layer erased the significance of surface effects.

GRASS-BASED agricultural management systems have the potential to sequester SOC and TN (Follett et al., 2001). Globally, grasslands comprise about 25% of the terrestrial surface (Sims and Risser, 2000). Grass management systems can increase C input and decrease C output compared with annual cropping systems resulting in a net increase in SOC storage (Gebhart et al., 1994). This net positive change may occur because of relatively undisturbed soil surfaces, perennial nature of many plant species, long growing season of mixed species, deep and long-lasting rooting system, and efficient water utilization throughout the year.

Estimates of potential C and N sequestration at depths below the traditional plow layer (i.e., 0.3-m depth) are few, but are needed to improve our understanding of management influences on greenhouse gas mitigation and nutrient cycling. A difference in SOC between adjacent cropland and a 5-yr-old conservation reserve grassland in the Great Plains USA was detected in various increments to 0.4-m soil depth, but not in depth increments from 0.4 to 3 m below the surface (Gebhart et

al., 1994). Summed to 1-m depth, SOC content was not different between cropland and conservation reserve. In a shortgrass-steppe with 56 yr of grazing in Colorado, SOC was not different between unharvested and lightly grazed rangeland at any soil depth increment to 0.9-m depth (Reeder et al., 2004). In contrast, SOC was greater in four of seven depth increments to 0.9-m depth under heavily grazed compared with unharvested rangeland. At the end of 12 yr of grazing on a previously ungrazed mixed-grass rangeland in Wyoming, SOC and TN were greater with light and heavy stocking than an ungrazed enclosure at a depth of 0 to 0.3 m, but statistically similar between treatments at a depth of 0 to 0.6 m (Schuman et al., 1999). These results suggest that SOC and TN sequestration are soil depth-, management-, and site-specific.

The effect of forage utilization regime on C and N accumulation in surface residue and the surface 6 cm of soil was highly significant during the first 4 yr of bermudagrass management in Georgia (Franzluebbers and Stuedemann, 2001; Franzluebbers et al., 2001). Rates of C and N sequestration in this near surface zone under grazed systems were more than double those under ungrazed systems. Whether these changes in SOC and TN near the surface were also occurring deeper in the profile was not determined. Since the perennial root system of bermudagrass can reach to a depth of 1 m, management of aboveground forage could affect belowground distribution of roots and subsequent accumulation of SOC and TN. On a Piedmont soil in Georgia, bermudagrass root distribution in the soil profile (0–1.5 m) was $87 \pm 4\%$ (mean \pm standard deviation) in the surface 0.3 m and $12 \pm 4\%$ in the 0.3- to 0.9-m depth (Carreker et al., 1977).

Most studies of profile SOC and TN have found few differences among management systems when summed to approximately 1 m, a typical rooting zone in many ecosystems (Gebhart et al., 1994; Schuman et al., 1999). Despite potential surface accumulation of SOC and TN with a particular management, consideration of the entire soil profile might reveal fewer differences due to (i) reversal of effects with depth or (ii) relatively low concentration and high natural variability of SOC and TN with depth resulting in little power to detect differences should they occur. Detection of differences due to management might be improved with sampling designs that take these variations into account.

One variable found to affect spatial distribution of SOC and TN in pastures is animal behavior. Under tall fescue (*Festuca arundinacea* Schreb.) in both Iowa (West et al., 1989) and Georgia (Franzluebbers et al., 2000), SOC and TN were greater within 10 m of shade

USDA-ARS, 1420 Experiment Station Road, Watkinsville, GA 30677-2373. Received 19 Apr. 2004. *Corresponding author (afranz@uga.edu).

Published in Soil Sci. Soc. Am. J. 69:1455–1462 (2005).
Soil & Water Management & Conservation
doi:10.2136/sssaj2004.0142

© Soil Science Society of America
677 S. Segoe Rd., Madison, WI 53711 USA

Abbreviations: LSD, least significant difference; SOC, soil organic carbon; TN, total nitrogen.

and water sources than zones farther away in <1-ha pastures. Accumulation of SOC and TN near shade and water sources was attributed to more frequent fecal deposition and greater plant growth.

Our objectives were to (i) quantify profile contents of SOC and TN at the beginning and end of 5 yr of 'Coastal' bermudagrass management on typical soils in the Southern Piedmont USA, (ii) evaluate whether stratification of pastures into zones delineated by animal behavior might improve detection of differences in SOC and TN with time due to management, and (iii) quantify variability in SOC and TN with depth.

MATERIALS AND METHODS

Site Characteristics

A 15-ha upland field (33°22' N, 83°24' W) in the Greenbrier Creek subwatershed of the Oconee River watershed near Farmington, GA had previously been conventionally cultivated with various row crops for several decades before grassland establishment by sprigging of 'Coastal' bermudagrass in 1991. Mean annual temperature is 16.5°C, rainfall is 1250 mm, and potential pan evaporation is 1560 mm. Dominant soils at the site were Madison, Cecil, and Pacolet sandy loam (fine, kaolinitic, thermic Typic Kanhapludults).

Experimental Design

The experimental design was a randomized complete block with treatments in a split-plot arrangement in each of three blocks, which were delineated by landscape features (i.e., slight, moderate, and severe erosion classes). Main plots were nutrient source ($n = 3$) and split-plots were forage utilization ($n = 4$) for a total of 36 experimental units. Grazed plots (i.e., paddocks) were 0.69 ± 0.03 ha. Spatial design of paddocks minimized runoff contamination and facilitated handling of cattle (*Bos taurus*) through a central roadway. Each paddock contained a 3×4 m shade, mineral feeder, and water trough placed in a line 15-m long at the highest elevation. Unharvested and hayed exclosures (100 m²) were placed side-by-side in paired low- and high-grazing pressure paddocks of each nutrient source.

Nutrient application was targeted to supply 200 kg N ha⁻¹ yr⁻¹ from one of three sources: (i) inorganic fertilizer as NH₄NO₃ broadcast in split applications in May and July, (ii) crimson clover (*Trifolium incarnatum* L.) cover crop plus supplemental inorganic fertilizer with half of the N assumed fixed by clover biomass and the other half as NH₄NO₃ broadcast in July, and (iii) chicken (*Gallus gallus*) broiler litter broadcast in split applications in May and July (Table 1).

Table 1. Characteristics and rates of fertilizer sources applied to 'Coastal' bermudagrass.

Variable	1994	1995	1996	1997	1998	5-yr mean
kg ha ⁻¹						
Inorganic nutrient source						
Total N	211	202	250	238	224	225
Clover + inorganic nutrient source†						
Total N	211	101	132	120	111	135
Broiler litter nutrient source‡						
Dry mass	5520	6500	5190	5020	5040	5390
Total C	1830	2050	1690	1930	1660	1830
Total N	195	216	164	223	172	194

† An additional 110 kg N ha⁻¹ yr⁻¹ was assumed to be released from biologically fixed N in clover cover crop biomass produced from 1995 to 1998.

‡ Broiler litter contained $26 \pm 4\%$ moisture on a gravimetric basis.

Forage utilization regime consisted of (i) unharvested biomass cut and left in place at the end of growing season, (ii) low grazing pressure targeted to maintain 3.0 Mg ha⁻¹ of forage, (iii) high grazing pressure targeted to maintain 1.5 Mg ha⁻¹ of forage, and (iv) hayed monthly to remove aboveground biomass at a 5-cm height. Yearling Angus steers grazed paddocks during a 140-d period from mid May until early October each year. Stocking density was 5.9 ± 2.1 and 8.4 ± 2.8 head ha⁻¹ under low and high grazing pressure, respectively (among nutrient sources, years, and 28-d periods). No grazing occurred in the winter. Animals were weighed, available forage determined, and paddocks restocked on a monthly basis. Readers are referred to Franzluebbers et al. (2004) for further details on nutrient application and forage management.

Sampling and Analyses

Soil was sampled in April 1994 and February 1999. Unharvested and hayed exclosures were not established until July 1994, and therefore, were not part of the sampling scheme at initiation. In April 1994, subsampling points within grazed paddocks were on a 30-m grid. Due to the nonuniform dimensions of paddocks, subsampling points within a paddock varied from four to nine, averaging 7 ± 1 . Point samples collected in 1994 ($n = 122$) were analyzed separately for C and N concentration and then data pooled before statistical analysis into approximate zones of 0- to 30-, 30- to 70-, and 70- to 120-m distances from shade to mimic zones used for collection in 1999. Pooling resulted in 2.3 ± 0.9 point subsamples per zone. In February 1999, subsampling locations within grazed paddocks were arranged along three semicircles, that is, at 5, 31 ± 3 , and 72 ± 10 m from shade/water. Along each of these semicircles, three cores were randomly collected and composited. Distance from shade/water varied somewhat in each paddock, because of the different shapes of the paddocks and the intent to create three equally sized zones in each paddock. Soil cores (4.1-cm diam) were extracted with a hydraulic probe mounted on a tractor and sectioned into depth units at 0.15, 0.3, 0.6, 0.9, 1.2, and 1.5 m. Surface residue was scraped to the side before sampling. Soil samples with roots were air-dried and ground to <2 mm in a mechanical grinder in 1994. In 1999, soil with roots was oven-dried (55°C, 72 h) and initially crushed to pass an 8-mm screen and subsequently a portion of the sample ground to <2 mm in a mechanical grinder before total C and N determinations.

Soil was analyzed for total C and N concentration with dry combustion at 1350°C (Leco CNS-2000, St. Joseph, MI).¹ Soil standards were used for calibration. It was assumed that total C was equivalent to SOC because soil pH was ≤ 6.5 at all soil depths. Samples were analyzed shortly after collection each year.

To verify some unexpected changes in SOC and TN during the 5-yr period, where analyses were determined separately in 1994 and in 1999, we analyzed all samples from both years simultaneously using near-infrared spectroscopy (Dalal and Henry, 1986). This alternative analysis technique was chosen based on the ease of determination, low cost for the large number of samples, and availability of dry combustion data for comparison. Data of SOC and TN were presented only derived from dry combustion, while those from near-infrared spectroscopy were used for verification only.

To assess nutrient source and forage utilization effects, data from multiple samples within an experimental unit were aver-

¹ Trade and company names are included for the benefit of the reader and do not imply any endorsement or preferential treatment of the product listed by the USDA.

aged and not considered a source of variation using the general linear models procedure (SAS Institute, 1990). Only to assess the impact of animal behavior on potential accumulation of SOC and N, was a separate analysis of variance conducted using zone (i.e., 0–30, 30–70, and 70–120 m from shade/water) and its interactions with nutrient source and forage utilization as sources of variation. Cumulative SOC and TN contents with depth (i.e., integrated from surface to specified depth) were calculated assuming bulk density of 1.3 Mg m^{-3} at 0 to 0.15 m, 1.4 Mg m^{-3} at 0.15 to 0.3 m, and 1.5 Mg m^{-3} at depths below 0.3 m. Some variation in bulk density among treatments, replications, and years of sampling may have occurred, but we did not expect it to be significant relative to changes in SOC and TN concentrations. Assumed bulk density values were based on observations from a nearby pasture study (Franzluebbbers et al., 2000). During the first 4 yr of this study, soil bulk density in the surface 6 cm was not affected by forage utilization (Franzluebbbers et al., 2001). Changes in SOC and TN contents during 5 yr were calculated from the difference between values in 1994 and 1999. Significant changes in SOC and TN (i.e., different from zero) were determined from the least-square-means output. Analysis of variance was conducted separately by depth (i.e., both incremental and cumulative) for SOC and TN concentration and content determined in 1999 (i.e., end of 5 yr) and for differences in SOC and TN content between years (i.e., net change) according to the split-plot design with three blocks. All effects were considered significant at $P \leq 0.1$. Although this was a lenient probability level, we did not want to overlook potentially important trends. Actual $\text{Pr} > F$ values for effects were also reported for many effects in tables.

RESULTS AND DISCUSSION

Soil Organic C and Total N Concentration at the End of Five Years

Soil organic C and TN concentration at the end of 5 yr of management were greatest at a depth of 0 to 0.15 m and decreased dramatically with depth (Tables 2 and 3). Differences in SOC and TN among treatments within depth increments were most significant at a depth of 0 to 0.15 m.

Addition of broiler litter supplied the equivalent (0- to 0.15-m depth) of 4.7 g C kg^{-1} soil during the 5 yr of study and was expected to result in higher SOC at the soil surface. However, neither SOC nor TN concentration were significantly affected by nutrient source at any soil depth, leading to the conclusion that broiler litter addition did not affect SOC sequestration in the soil profile during these 5 yr. Our results are consistent with other reports that have shown no difference in SOC concentration due to broiler litter application in the southeastern USA (Jackson et al., 1977; Wood et al., 1996; Franzluebbbers et al., 2001). Perhaps during a longer period of time, significant SOC sequestration with broiler litter addition could be achieved. Kingery et al. (1994) found greater SOC concentration under pastures in Alabama fertilized with than without broiler litter at the end of 21 ± 4 yr, although the rate of sequestration was only approximately 8% of that applied. During 56 yr of manure application in Oregon, SOC sequestration was 23% of that applied (Collins et

Table 2. Soil organic C concentration within individual depth increments and soil organic C content summed across depths as affected by nutrient source and forage utilization at the end of 5 yr of management in February 1999.

Nutrient source	Forage utilization	Incremental depth, m						Cumulative depth, m		
		0–0.15	0.15–0.3	0.3–0.6	0.6–0.9	0.9–1.2	1.2–1.5	0–0.3	0–0.9	0–1.5
		g kg ^{−1}						Mg ha ^{−1}		
Inorganic	unharvested	15.2	4.8	2.0	1.2	0.7	0.5	39.7	53.9	59.5
Inorganic	low grazing pressure	17.2	5.0	2.2	1.0	0.8	0.5	44.0	58.5	64.4
Inorganic	high grazing pressure	14.3	4.9	2.4	1.1	0.9	0.6	38.3	53.9	60.5
Inorganic	hayed	12.8	4.9	2.4	1.2	0.9	0.5	35.2	51.4	57.8
Clover + inorganic	unharvested	13.2	6.1	2.8	1.6	0.8	0.5	38.4	57.9	64.0
Clover + inorganic	low grazing pressure	17.2	6.4	2.5	1.2	0.8	0.5	47.1	63.8	70.0
Clover + inorganic	high grazing pressure	17.3	5.0	2.4	1.2	0.7	0.6	44.3	60.3	65.8
Clover + inorganic	hayed	11.5	6.7	2.8	1.4	0.7	0.6	36.5	55.1	60.8
Broiler litter	unharvested	19.2	4.7	2.6	1.3	0.8	0.6	47.3	64.8	71.1
Broiler litter	low grazing pressure	16.2	5.4	2.2	1.2	0.8	0.6	43.0	58.5	64.6
Broiler litter	high grazing pressure	16.6	4.5	2.2	1.1	0.8	0.6	41.8	56.8	62.7
Broiler litter	hayed	13.9	4.0	2.4	1.2	0.6	0.5	35.6	51.8	56.8
LSD (<i>P</i> = 0.1) among nutrient × utilization		2.8 [‡]	2.6	1.1	0.6	0.3	0.2	7.2	12.9	13.9
Inorganic	mean	14.9	4.9	2.2	1.1	0.8	0.5	39.3	54.4	60.6
Clover + inorganic	mean	14.8	6.1	2.6	1.3	0.8	0.5	41.6	59.3	65.1
Broiler litter	mean	16.5	4.7	2.3	1.2	0.7	0.6	41.9	58.0	63.8
LSD (<i>P</i> = 0.1) among nutrient means		4.0	2.8	1.1	0.5	0.3	0.2	13.2	17.4	19.3
Mean	unharvested	15.9	5.2	2.4	1.4	0.8	0.5	41.8	58.9	64.9
Mean	low grazing pressure	16.9	5.6	2.3	1.2	0.8	0.5	44.7	60.3	66.3
Mean	high grazing pressure	16.1	4.8	2.3	1.1	0.8	0.6	41.5	57.0	63.0
Mean	hayed	12.7	5.2	2.5	1.3	0.7	0.5	35.8	52.8	58.5
LSD (<i>P</i> = 0.1) among utilization means		1.6 [‡]	1.5	0.7	0.3	0.2	0.1	4.2 [‡]	7.4	8.0
Coefficient of variation, %		13	35	34	34	29	25	12	16	16
Source of variation	df	Pr > F								
Nutrient source (NS)	2	0.63	0.57	0.74	0.74	0.74	0.94	0.90	0.86	0.89
Forage utilization (FU)	3	0.002	0.81	0.94	0.62	0.90	0.92	0.01	0.35	0.38
FU1: Grazed vs. not	1	0.004	0.96	0.57	0.22	0.82	0.60	0.02	0.37	0.37
FU2: Unharv vs. hayed	1	0.004	0.98	0.87	0.68	0.51	0.91	0.02	0.17	0.19
FU3: Low vs. high grazing pressure	1	0.41	0.35	0.91	0.80	0.83	0.68	0.19	0.45	0.49
NS × FU	6	0.05	0.95	0.99	0.99	0.76	0.88	0.39	0.90	0.90

† Next to LSD value indicates significance among comparisons based on preplanned orthogonal contrasts.

al., 1992). With 135 yr of continuous farmyard manure application in England, SOC sequestration was 17% of that applied (Webster and Goulding, 1989).

When averaged across nutrient sources, effects of forage utilization were significant only for the 0- to 0.15-m depth for SOC concentration (Table 2) and for the 0- to 0.15-, 0.6- to 0.9-, and 0.9- to 1.2-m depths for TN concentration (Table 3). At a depth of 0 to 0.15 m, SOC and TN concentration were lower under haying than under unharvested and both grazing pressures (i.e., concentrations under haying were $74 \pm 5\%$ of those under other management systems). The lower SOC and TN concentrations with haying were also reported from this same study from shallow (0–6 cm) surface samples collected on a yearly basis (Franzluebbers and Stuedemann, 2001; Franzluebbers et al., 2001). Haying removed above-ground forage from the field, whereas unharvested and grazed pastures allowed return of either whole or partially digested forage to the soil where it could be converted to soil organic matter by soil microorganisms.

At a depth of 0.6 to 1.2 m, TN concentration was greater under unharvested than under grazed treatments when averaged across nutrient sources (Table 3). Deep forage rooting may have been enhanced when forage was allowed to accumulate aboveground vegetation. It may be that the slow decomposition of roots at these depths contributed to TN accumulation under unharvested management. In general SOC and TN responded similarly to management, but the detection of differences in TN with soil depth suggests that fertiliza-

tion with an adequate level of N (i.e., $200 \text{ kg ha}^{-1} \text{ yr}^{-1}$) may have improved the nutritional status for soil microbial activity at lower depths, such that N moving through the profile could have stimulated mineralization of C and subsequent sequestration of organic N into stable organic compounds. Although differences in C/N ratio among treatments were rare at any depth within a sampling event, C/N ratio was reduced in 1999 compared with 1994 at all depths, except at 1.2 to 1.5 m (data not shown). The C/N ratio was 17.7 ± 1.5 in 1994 and 14.6 ± 3.1 in 1999 (among depths to 1.2 m). These data suggest that the input of fertilizer N reduced C/N ratio by increasing organic N in the profile.

Retention of forage on pasture either as unharvested conservation reserve or through season-long cattle grazing was important for increasing SOC and TN concentrations compared with forage removal (Tables 2 and 3). Removal of forage as hay not only reduced the input of C and N from residues at the soil surface, but also may have limited rooting depth and activity below the immediate soil surface due to senescent-inducing signals from regularly clipped aboveground vegetation (Morgan and Brown, 1983).

Lack of difference in profile SOC and TN between unharvested and grazed systems contrasted with greater SOC and TN under grazed than unharvested management at a depth of 0 to 6 cm (Franzluebbers and Stuedemann, 2001; Franzluebbers et al., 2001), suggesting that grazing had only superficial effects on SOC and TN. From five sites in the Great Plains USA, SOC content

Table 3. Total soil N concentration within individual depth increments and total soil N content summed across depths as affected by nutrient source and forage utilization at the end of 5 yr of management in February 1999.

Nutrient source	Forage utilization	Incremental depth, m						Cumulative depth, m		
		0–0.15	0.15–0.3	0.3–0.6	0.6–0.9	0.9–1.2	1.2–1.5	0–0.3	0–0.9	0–1.5
		g kg ⁻¹						Mg ha ⁻¹		
Inorganic	unharvested	1.09	0.35	0.12	0.10	0.08	0.05	2.85	3.82	4.39
Inorganic	low grazing pressure	1.18	0.33	0.12	0.10	0.07	0.05	3.01	3.97	4.51
Inorganic	high grazing pressure	0.96	0.32	0.11	0.07	0.07	0.02	2.54	3.39	3.82
Inorganic	hayed	0.87	0.28	0.12	0.12	0.08	0.04	2.28	3.40	3.94
Clover + inorganic	unharvested	0.78	0.34	0.13	0.15	0.11	0.07	2.24	3.53	4.32
Clover + inorganic	low grazing pressure	1.21	0.34	0.13	0.10	0.08	0.03	3.08	4.09	4.60
Clover + inorganic	high grazing pressure	1.26	0.34	0.14	0.11	0.07	0.06	3.17	4.28	4.87
Clover + inorganic	hayed	0.65	0.36	0.15	0.12	0.08	0.05	2.03	3.21	3.78
Broiler litter	unharvested	1.31	0.30	0.17	0.13	0.09	0.03	3.20	4.58	5.14
Broiler litter	low grazing pressure	1.13	0.36	0.13	0.11	0.07	0.05	2.96	4.01	4.55
Broiler litter	high grazing pressure	1.19	0.29	0.14	0.10	0.08	0.04	2.92	3.97	4.51
Broiler litter	hayed	0.87	0.27	0.12	0.10	0.06	0.06	2.24	3.23	3.78
LSD (<i>P</i> = 0.1) among nutrient × utilization		0.25‡	0.10	0.06	0.05	0.03	0.04	0.50‡	0.70‡	0.84
Inorganic	mean	1.03	0.32	0.12	0.10	0.07	0.04	2.67	3.64	4.17
Clover + inorganic	mean	0.97	0.35	0.14	0.12	0.09	0.05	2.63	3.78	4.39
Broiler litter	mean	1.12	0.31	0.14	0.11	0.08	0.05	2.83	3.95	4.50
LSD (<i>P</i> = 0.1) among nutrient means		0.34	0.11	0.04	0.04	0.03	0.02	0.84	1.12	1.23
Mean	unharvested	1.06	0.33	0.14	0.13	0.09	0.05	2.76	3.98	4.62
Mean	low grazing pressure	1.17	0.34	0.12	0.10	0.07	0.04	3.02	4.02	4.55
Mean	high grazing pressure	1.13	0.32	0.13	0.09	0.07	0.04	2.88	3.88	4.40
Mean	hayed	0.79	0.30	0.13	0.11	0.07	0.05	2.19	3.28	3.84
LSD (<i>P</i> = 0.1) among utilization means		0.15‡	0.06	0.03	0.03‡	0.02‡	0.02	0.29‡	0.40‡	0.49‡
Coefficient of variation, %		17	22	30	33	27	60	13	13	14
Source of variation	df	Pr > F								
Nutrient source (NS)	2	0.66	0.74	0.48	0.64	0.70	0.54	0.87	0.85	0.85
Forage utilization (FU)	3	0.001	0.65	0.83	0.21	0.24	0.81	0.001	0.02	0.05
FU1: Grazed vs. not	1	0.001	0.58	0.51	0.06	0.24	0.35	0.001	0.06	0.23
FU2: Unharv vs. hayed	1	0.006	0.42	0.57	0.33	0.09	0.97	0.003	0.008	0.01
FU3: Low vs. high grazing pressure	1	0.64	0.42	0.78	0.71	0.95	0.87	0.42	0.55	0.59
NS × FU	6	0.04	0.82	0.80	0.75	0.76	0.46	0.07	0.17	0.40

† Next to LSD value indicates significance among comparisons based on preplanned orthogonal contrasts.

was greater under unharvested forage than under cropland at depth increments to 0.4 m, but not below this depth (Gebhart et al., 1994).

Soil Organic C and Total N Changes with Time Due to Management

Having determined initial profile SOC and TN allowed us to calculate the change in SOC and TN with time, although initial values were only available for low and high grazing pressure treatments under each of the nutrient source regimes. The single measurement of SOC and TN concentration at the end of 5 yr relied on randomly placed treatments to overcome the natural variability in these soil properties to determine relative management effects. Initial SOC and TN concentration are needed to directly estimate SOC and TN sequestration with time. In addition, temporal variations in SOC and TN can be more explicitly separated from spatial variations. Using LSD values at 0- to 0.3-, 0- to 0.9-, and 0- to 1.5-m depths (Mg ha^{-1}), random variation of the absolute difference in SOC and TN (Table 4) between two times was $77 \pm 24\%$ of the relative difference in SOC (Table 2) and TN (Table 3) among treatments at one time. Therefore, not only was the difference in SOC and TN with time necessary to obtain rates of SOC and TN sequestration, it also reduced the LSD to be able to detect smaller differences among treatments.

Changes in SOC and TN with time were not affected by nutrient source at any depth when averaged across forage utilization regimes (Table 4). This result verified that the additional C added with broiler litter, as well as the form of N supplied, had no distinguishable effect on SOC and TN sequestration.

Averaged across nutrient sources, there was no effect of grazing pressure on net change in SOC and TN with time at any depth (Table 4). However, significant sequestration of SOC and TN occurred under nearly all

management systems to at least 0.3 m and sometimes to as much as 1.5-m depth. At a depth of 0 to 0.3 m, sequestration of SOC was $6.2 \pm 2.0 \text{ Mg ha}^{-1}$ (among nutrient source and forage utilization regimes) and sequestration of TN was $0.64 \pm 0.17 \text{ Mg ha}^{-1}$. Below the 0.3-m depth, differences in SOC between 1994 and 1999 among the 24 combinations of nutrient source-forage utilization-depth increment were less than zero in six cases and not different from zero in all other cases (data not shown). All of the declines in SOC concentration between 1994 and 1999 that were detected with dry combustion were corroborated with values that were equally or more negative using near-infrared spectroscopy. For TN, three cases were less than zero and two cases were greater than zero. Therefore with increasing soil depth below the surface 0.3 m, there was some, but overall, little tendency for loss of SOC and TN with time.

Sequestration of SOC in the 0- to 0.3-m depth on a yearly basis was $1.2 \pm 0.4 \text{ Mg ha}^{-1} \text{ yr}^{-1}$ (among the six combinations of nutrient source and forage utilization) (Table 4). From yearly samples of the surface 6 cm of soil in this same study, the estimate of SOC sequestration was $1.4 \pm 0.2 \text{ Mg ha}^{-1} \text{ yr}^{-1}$ among the same group of treatments (Franzluebbbers et al., 2001), indicating that most C sequestration occurred near the soil surface. The two estimates of SOC sequestration agreed reasonably well, although both treatment and random variation were greater in the current investigation based on deep sampling. The $\text{LSD}_{(P=0.1)}$ for SOC sequestration at a depth of 0 to 0.3 m in the current investigation was $1.1 \text{ Mg ha}^{-1} \text{ yr}^{-1}$ (Table 4), while the $\text{LSD}_{(P=0.1)}$ for SOC sequestration at a depth of 0 to 6 cm in the study based on yearly analysis was $0.3 \text{ Mg ha}^{-1} \text{ yr}^{-1}$. Therefore, the more intensive sampling protocol of surface soil allowed a more precise estimate.

Although estimates of net change in profile SOC generally declined with depth, the switch from significant

Table 4. Net change in soil organic C and total soil N content summed across depths as affected by nutrient source and forage utilization during 5 yr of management from April 1994 to February 1999.

		Soil organic C					Total soil N				
		Soil depth, m									
Nutrient source	Forage utilization	0–0.3	0–0.6	0–0.9	0–1.2	0–1.5	0–0.3	0–0.6	0–0.9	0–1.2	0–1.5
		Mg ha ^{−1}									
Inorganic	low grazing pressure	8.1†	7.1†	6.3†	6.2†	5.5	0.89†	0.79†	0.84†	0.92†	0.95†
Inorganic	high grazing pressure	5.5†	4.1	2.9	2.0	0.7	0.45†	0.29	0.32	0.45	0.40
Clover + inorganic	low grazing pressure	8.6†	7.5†	5.0	4.7	4.1	0.56†	0.33	0.27	0.35	0.25
Clover + inorganic	high grazing pressure	6.8†	2.5	1.0	−0.5	−1.6	0.80†	0.52†	0.58†	0.60	0.64
Broiler litter	low grazing pressure	4.2†	1.2	−0.5	−1.7	−3.1	0.53†	0.28	0.35	0.42	0.43
Broiler litter	high grazing pressure	3.7	3.6	3.2	2.8	2.2	0.60†	0.62†	0.77†	0.79†	0.79†
LSD (<i>P</i> = 0.1) among nutrient × utilization		5.6	7.4	7.6	8.3	9.2	0.41	0.65	0.80	0.91	1.00
Inorganic	mean	6.8†	5.6†	4.6	4.1	3.1	0.67†	0.54†	0.58†	0.68†	0.67†
Clover + inorganic	mean	7.7†	5.0	3.0	2.1	1.3	0.68†	0.43	0.43	0.48	0.44
Broiler litter	mean	3.9	2.4	1.4	0.6	−0.5	0.56†	0.45	0.56†	0.61†	0.61†
LSD (<i>P</i> = 0.1) among nutrient means		5.9	7.7	8.6	9.7	10.2	0.57	0.69	0.74	0.73	0.77
Mean	low grazing pressure	7.0†	5.3†	3.6†	3.1	2.2	0.66†	0.47†	0.49†	0.56†	0.54†
Mean	high grazing pressure	5.3†	3.4†	2.4	1.4	0.4	0.62†	0.48†	0.56†	0.62†	0.61†
LSD (<i>P</i> = 0.1) among utilization means		3.2	4.3	4.4	4.8	5.3	0.24	0.38	0.46	0.53	0.58
Source of variation		df	Pr > F								
Nutrient source (NS)		2	0.44	0.67	0.75	0.75	0.77	0.90	0.93	0.89	0.84
Forage utilization (FU)		1	0.36	0.44	0.60	0.52	0.54	0.74	0.96	0.78	0.85
NS × FU		2	0.88	0.43	0.36	0.28	0.27	0.14	0.25	0.28	0.44

† Next to mean indicates significance from zero at $P \leq 0.1$.

effects near the soil surface to nonsignificant effects at lower depths appeared to be as much due to increased random variation as due to less actual change. For every 0.3 m of soil below the plow layer, the change in SOC and TN content would have had to become an average of 0.6 and 0.10 Mg ha⁻¹ greater, respectively, to maintain significance at $P = 0.1$. Therefore, a hypothetical change in SOC of 4 Mg ha⁻¹ to meet significance at $P = 0.1$ would have been declared not significant if diluted with soil from deeper in the profile, even if no other change below this depth occurred. To achieve significantly positive SOC and TN sequestration at a depth of 0 to 1.5 m, rates ≥ 1.3 and 0.14 Mg ha⁻¹ yr⁻¹, respectively, were required. Although possible, such high rates of SOC and TN sequestration are rarely achieved in forage management systems (Follett et al., 2001).

The coefficient of variation in SOC concentration among individual soil cores increased from $37 \pm 13\%$ in the surface 0.3 m to $83 \pm 26\%$ below the 0.3-m depth (Fig. 1). By combining data from the 7 ± 1 subsamples collected within a paddock in 1994 into three zones (i.e., 0–30, 30–70, and 70–120 m from shade/water), the coefficient of variation was reduced to 10, 8, 18, 40, 35, and 17% at 0 to 0.15, 0.15 to 0.3, 0.3 to 0.6, 0.6 to 0.9, 0.9 to 1.2, and 1.2 to 1.5 m, respectively. To obtain more precise estimates of SOC for a given management system, it seems necessary to composite a number of subsamples for adequate representation. Compositing cores in the field to represent a management unit would require the same amount of labor in the field as collecting and analyzing individual cores, but would save time and operating expenses in the laboratory without sacrificing accuracy of determination.

The very low SOC concentration below 0.3 m, suggests at first glance, an opportunity to potentially sequester greater quantity of SOC deep in the profile. However, due to the warm-humid climatic conditions of the region that favor organic matter decomposition, this opportunity may be difficult to realize. Only if sufficient C input

were made available deep in the profile, such as via greatly enhanced rooting activity, would a significant change in SOC at lower soil depths be possible. Considering that the surface 0.3 m of soil contained the majority of profile SOC and TN (i.e., 65 ± 3 and $62 \pm 5\%$ of the C and N in the 0 to 1.5-m profile, respectively) and that concentrations below the surface were relatively stable, then our ability to detect feasible changes in SOC and TN at lower depths may be seriously challenged. Feasible changes with agricultural management should consider the practicality of sequestering C and N. Easily controlled management variables affecting change at the soil surface should be considered along with more difficult management scenarios affecting change at lower depths. For example, increasing SOC and TN contents at the surface may be as practical as switching from inversion tillage to no tillage on cropland (Paustian et al., 2000; West and Marland, 2002) or allowing cattle to graze pastures rather than cutting for hay (Franzluebbers et al., 2001). Planting of deep-rooted crops has been proposed to affect SOC storage deeper in the profile (Fisher et al., 1994), but developing economic opportunities and ecological niches for such systems make them less practical. More research is needed to explore management options that could affect surface and subsurface C and N pools.

Soil Organic C and Total N Changes with Time Due to Pasture Zone

Profile SOC and TN contents were affected by pasture zone, primarily due to effects that occurred near the surface (Fig. 2 and 3). In the zone nearest shade/water (i.e., 0–30 m), the change in profile SOC and TN was significant at all depths, except below 0.3 m for SOC under low grazing pressure. At a depth of 0 to 0.15 m, SOC and TN sequestration were 3.8 ± 3.2 and 0.41 ± 0.23 Mg ha⁻¹ greater than in other zones (i.e., 30–70 and 70–120 m from shade/water). Cattle spend more time near shade and water sources, depositing more feces and spoiling more forage in these areas. This animal behavior was a likely reason for preferential accumulation of SOC near shade and water sources, a result similar to that reported in other grazing studies (West et al., 1989; Franzluebbers et al., 2000).

In the middle zone (i.e., 30 to 70 m from shade/water), the change in profile TN was generally positive (Fig. 3), but the change in profile SOC was not different from zero, except at the surface (Fig. 2). In the zone farthest from shade/water (i.e., 70 to 120 m), changes in profile SOC and TN were positive under low grazing pressure, but not different from zero under high grazing pressure. The differential response in profile SOC and TN due to grazing pressure as a function of distance from shade and water sources is curious, because cattle grazing pastures with low forage mass (i.e., high grazing pressure) have been observed to spend up to an hour more per day grazing than with high forage mass (Forbes and Coleman, 1985). If more grazing periods were to have occurred each day, it is possible that a greater frequency of fecal deposition near shade/water could have oc-

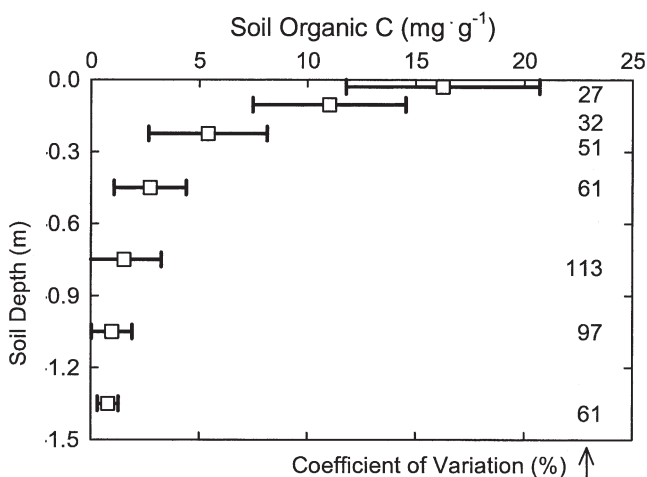


Fig. 1. Organic C concentration (mean \pm standard deviation) in the soil profile from individual analyses of 122 cores collected at the initiation of the experiment in April 1994. Depths sampled were 0 to 0.06, 0.06 to 0.15, 0.15 to 0.3, 0.3 to 0.6, 0.6 to 0.9, 0.9 to 1.2, and 1.2 to 1.5 m.

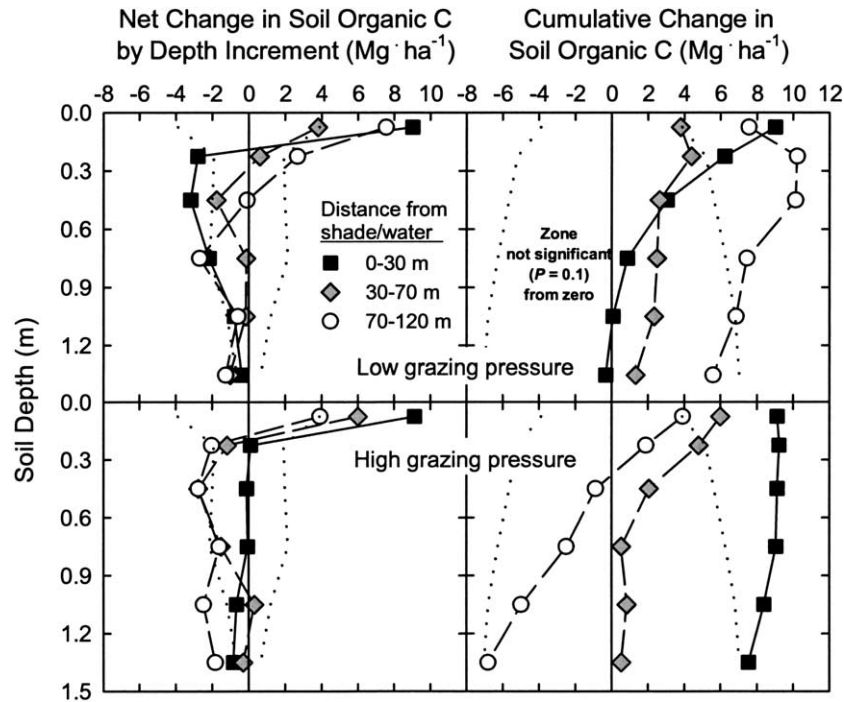


Fig. 2. Net change in soil organic C content by depth and cumulatively in the profile as affected by distance from shade/water and forage utilization from 1994 to 1999. Data points falling in the zone between 0 and the dotted line are not significantly different from zero at $P = 0.1$.

curred, since excretion typically follows resting periods. The number of grazing periods per day was reduced from typically four to three by forage antiquality factors (i.e., ergot alkaloids) found in tall fescue (Seman et al., 1997, 1999), but it is not clear in our study that forage mass under continuous stocking would have affected forage quality and subsequent grazing cycles. Animal behavior effects on soil-profile changes in SOC and

TN deserve more attention in the future, if site-specific recommendations for management are to be implemented.

Although inorganic N did accumulate in the soil profile during these 5 yr of some management systems ($8 \pm 8 \text{ kg ha}^{-1} \text{ yr}^{-1}$) (Franzluebbbers and Stuedemann, 2003), the estimated portion of profile TN increase from inorganic N was $1 \pm 14\%$ (among nutrient source-pasture

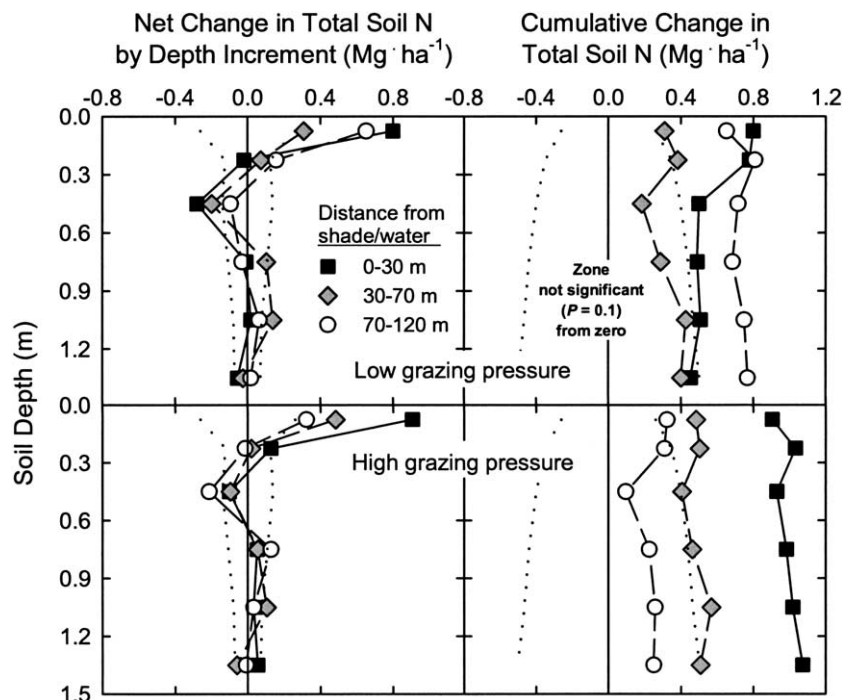


Fig. 3. Net change in total soil N content by depth and cumulatively in the profile as affected by distance from shade/water and forage utilization from 1994 to 1999. Data points falling in the zone between 0 and the dotted line are not significantly different from zero at $P = 0.1$.

zone combinations). Most of the TN increase, therefore, was due to organic N accumulation.

CONCLUSIONS

Soil-profile organic C and TN at the end of 5 yr of management were not affected by nutrient source, but were lower when bermudagrass was harvested as hay than when grazed by cattle or left unharvested. Under grazed management systems, SOC and TN sequestration occurred primarily at a depth of 0 to 0.15 m. However, small losses with depth, combined with increasing natural variability with depth, led to nonsignificant changes in SOC (0- to 1.5-m depth) in all six management systems evaluated. Sequestration of TN within the 0- to 1.5-m profile was significant, but not different among management systems. High natural variability in profile SOC and TN could be partly reduced by (i) compositing soil cores from representative management zones within a pasture, (ii) determining concentrations at more than one time, and (iii) restricting calculations to a reasonable depth coinciding with plant rooting activity. For example by limiting calculations of SOC and TN sequestration to a depth of 0 to 0.9 m (the dominant rooting zone of bermudagrass), significant changes could be detected, averaging 0.6 ± 0.5 (SOC) and 0.09 ± 0.04 (TN) $\text{Mg ha}^{-1} \text{yr}^{-1}$ (among nutrient source and forage utilization regimes), respectively.

ACKNOWLEDGMENTS

We appreciate the technical expertise of Steven Knapp, David Lovell, Robert Martin, Heather Hart, Devin Berry, Anthony Dillard, Dwight Seman, Fred Hale, Robert Sheats, and Clara Parker. We appreciate the assistance of Drs. Rus Bruce and Stan Wilkinson in helping to initiate the study and of Dr. Dwight Fisher in providing analyses with near infrared spectroscopy.

REFERENCES

- Carreker, J.R., S.R. Wilkinson, A.P. Barnett, and J.E. Box. 1977. Soil and water management systems for sloping land. USDA, Agric. Res. Serv., ARS-S-160. U.S. Gov. Print. Office, Washington, DC.
- Collins, H.P., P.E. Rasmussen, and C.L. Douglas, Jr. 1992. Crop rotation and residue management effects on soil carbon and microbial dynamics. *Soil Sci. Soc. Am. J.* 56:783–788.
- Dalal, R.C., and R.J. Henry. 1986. Simultaneous determination of moisture, organic carbon, and total nitrogen by near infrared reflectance spectrophotometry. *Soil Sci. Soc. Am. J.* 50:120–123.
- Fisher, M.J., I.M. Rao, M.A. Ayarza, C.E. Lascano, J.I. Sanz, R.J. Thomas, and R.R. Vera. 1994. Carbon storage by introduced deep rooted grasses in the South American savannas. *Nature (London)* 371:236–238.
- Follett, R.F., J.M. Kimble, and R. Lal. 2001. The potential of U.S. grazing lands to sequester carbon and mitigate the greenhouse effect. *Lewis Publ., Boca Raton, FL*.
- Forbes, T.D.A., and S.W. Coleman. 1985. Influence of herbage mass and structure of warm-season grass on ingestive behavior of grazing cattle. p. 1123–1125. *In* Proc. XV Int. Grassland Congr., Kyoto, Japan.
- Franzluebbers, A.J., and J.A. Stuedemann. 2001. Bermudagrass management in the Southern Piedmont USA: IV. Soil-surface nitrogen pools. *The Scientific World* 1(S2):673–681.
- Franzluebbers, A.J., and J.A. Stuedemann. 2003. Bermudagrass management in the Southern Piedmont USA: VI. Soil-profile inorganic nitrogen. *J. Environ. Qual.* 32:1316–1322.
- Franzluebbers, A.J., J.A. Stuedemann, and H.H. Schomberg. 2000. Spatial distribution of soil carbon and nitrogen pools under grazed tall fescue. *Soil Sci. Soc. Am. J.* 64:635–639.
- Franzluebbers, A.J., J.A. Stuedemann, and S.R. Wilkinson. 2001. Bermudagrass management in the Southern Piedmont USA. I. Soil and surface residue carbon and sulfur. *Soil Sci. Soc. Am. J.* 65:834–841.
- Franzluebbers, A.J., S.R. Wilkinson, and J.A. Stuedemann. 2004. Bermudagrass management in the Southern Piedmont USA: X. Coastal productivity and persistence in response to fertilization and defoliation regimes. *Agron. J.* 96:1400–1411.
- Gebhart, D.L., H.B. Johnson, H.S. Mayeux, and H.W. Polley. 1994. The CRP increases soil organic carbon. *J. Soil Water Conserv.* 49:488–492.
- Jackson, W.A., S.R. Wilkinson, and R.A. Leonard. 1977. Land disposal of broiler litter: Changes in concentration of chloride, nitrate nitrogen, total nitrogen, and organic matter in a Cecil sandy loam. *J. Environ. Qual.* 6:58–62.
- Kingery, W.L., C.W. Wood, D.P. Delaney, J.C. Williams, and G.L. Mullins. 1994. Impact of long-term land application of broiler litter on environmentally related soil properties. *J. Environ. Qual.* 23:139–147.
- Morgan, J.A., and R.H. Brown. 1983. Photosynthesis and growth of bermudagrass swards. II. Growth patterns as estimated by harvest and gas exchange techniques. *Crop Sci.* 23:352–357.
- Paustian, K., J. Six, E.T. Elliott, and H.W. Hunt. 2000. Management options for reducing CO₂ emissions from agricultural soils. *Bio-geochemistry* 48:147–163.
- Reeder, J.D., G.E. Schuman, J.A. Morgan, and D.R. LeCain. 2004. Response of organic and inorganic carbon and nitrogen to long-term grazing of the shortgrass steppe. *Environ. Manage.* 33:485–495.
- SAS Institute. 1990. SAS user's guide: Statistics. Version 6 ed. SAS Inst., Cary, NC.
- Schuman, G.E., J.D. Reeder, J.T. Manley, R.H. Hart, and W.A. Manley. 1999. Impact of grazing management on the carbon and nitrogen balance of a mixed-grass rangeland. *Ecol. Appl.* 9:65–71.
- Seman, D.H., J.A. Stuedemann, and J.E. Anderson. 1997. Spectral analysis of bovine grazing behavior on *Neotyphodium coenophialum* infested tall fescue. *Appl. Anim. Behav. Sci.* 54:73–87.
- Seman, D.H., J.A. Stuedemann, and N.S. Hill. 1999. Behavior of steers grazing monocultures and binary mixtures of alfalfa and tall fescue. *J. Anim. Sci.* 77:1402–1411.
- Sims, P.L., and P.G. Risser. 2000. Grasslands. p. 323–356. *In* M.G. Barbour and W.G. Billings (ed.) *North American terrestrial vegetation*. 2nd ed. Cambridge Univ. Press, New York.
- Webster, C.P., and K.W.T. Goulding. 1989. Influence of soil carbon content on denitrification from fallow land during autumn. *J. Sci. Food Agric.* 49:131–142.
- West, C.P., A.P. Mallarino, W.F. Wedin, and D.B. Marx. 1989. Spatial variability of soil chemical properties in grazed pastures. *Soil Sci. Soc. Am. J.* 53:784–789.
- West, T.O., and G. Marland. 2002. A synthesis of carbon sequestration, carbon emissions, and net carbon flux in agriculture: Comparing tillage practices in the United States. *Agric. Ecosyst. Environ.* 91:217–232.
- Wood, B.H., C.W. Wood, K.H. Yoo, K.S. Yoon, and D.P. Delaney. 1996. Nutrient accumulation and nitrate leaching under broiler litter amended corn fields. *Commun. Soil Sci. Plant Anal.* 27:2875–2894.